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FATIGUE STRENGTH OF FLUSH-RIVETED JOINTS FOR AIRCRAFT MANUFACTURED BY VARIOUS RIVETING METHODS

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NACA

WASHINGTON

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SUMMARY

The results of an investigation to determine the fatigue strength of flush-riveted joints manufactured by different riveting methods are presented. Tests were made on a direct stress fatigue machine at room temperatures. The rivets were made of aluminum alloy A17S-T and the plates of aluminum alloy 24S-T. Preliminary tests at 70° F on specimens having varying ratios of rivet diameter to plate thickness were made under both static and dynamic loads to check the efficiency of the specimen grips.

The results of the tests showed that the fatigue strength of the joints was directly affected by the method of riveting used. The endurance limit of the rivets in completely reversed shear was greatest for commercial countersunk rivets with the head 0.010 inch above the plate surface before driving, while the endurance limit was lowest for commercial countersunk rivets with the head 0.003 inch below the surface before driving. The endurance limit for reverse-driven rivets (Method E) was intermediate between the extremes. In several cases considerable variation in behavior under the same fatigue loads was found in specimens of the same series. The lowest endurance limit found in this investigation was about 9400 psi while the maximum found was about 15,000 psi. Static tests on the reverse driven rivets showed an ultimate strength of about 38,000 psi, this being the highest strength developed by any of the joints.

DEFINITIONS

The joints were tested in tension, thus putting the rivets in shear. The term "ultimate tensile strength" as used in this report refers to the ultimate strength of the joints as a unit. The term "static ultimate strength" of the rivets refers to the ultimate shearing unit stress developed by the rivets at rupture. The term "unit stress" in this report refers to the shearing unit stress in the rivets.

INTRODUCTION

Tests by Hartmann, Lyst, and Andrews (reference 1) and by Andrews and Holt (reference 2) on aluminum alloy riveted connections have recently been published. The literature on fatigue tests of riveted joints is still meager, however, and so far as the authors know an investigation of the size and the type of aluminum alloy rivets here studied has not previously been made. After some preliminary study, it was decided to limit the scope of the investigation to one size of rivet, one thickness of plate, one type of specimen, and four methods of riveting. (See fig. 1.)

This investigation, conducted at the Northwestern University, was sponsored by and conducted with the financial assistance of the National Advisory Committee for Aeronautics. The methods of riveting investigated are those for which static strength has been investigated by the Langley Memorial Aeronautical Laboratory of the National Advisory Committee for Aeronautics. (See reference 3.) The work was conducted under the direction of the authors.

Credit for performing most of the actual testing should be given to the following students: Helmut Abt, Victor Archer, Gervase Gauer, Paul Gouwens, Kenneth Lenzen, Frank Phalen, William Ross, and Miles Tourtellotte. The work of remodeling and calibrating the testing machine was done by L. T. Wyly.

APPARATUS AND METHODS

Riveting methods.- The methods of riveting used are those developed by the Langley structures research laboratory of the NACA and described in reference 3. The types of rivets used and their dimensions, the angles of the countersunk holes, and the side from which the rivets are inserted are shown in figures 2 to 5. The distinguishing features of the riveting methods used in this investigation are:

Method C. The manufactured head of the countersunk rivet is driven with a vibrating gun while the shank end is bucked with a bar. The driven rivet head is flat. All specimens riveted by this method are given the prefix C in the designation.

Method N. The manufactured round head of the rivet is driven with a vibrating gun while the shank end is bucked with a bar. After the rivet is driven, the portion of the formed head that protrudes above the skin surface is milled off and finished smooth with the sheet. All specimens riveted by this method have the prefix N.

<u>Test specimens</u>.- Details of the specimens for the "Preliminary Tests" are shown in figure 6. Details of the specimens for the "Main Tests" are shown in figure 1. The preliminary specimens were detailed by the Northwestern University. The Langley laboratory made the final details of the main test specimens and furnished all specimens for both preliminary and regular tests.

<u>Materials</u>.- The plates were made from sheets of 24S-T aluminum alloy. The rivets were made from A17S-T aluminum alloy.

<u>Specimen grips</u>.- The grips used to mount the specimens in the testing machines are split screw fittings which were secured to the ends of the specimens by drive fit dowels, by friction, and by split tapered dowels. Details are shown in figure 7.

<u>Testing machines</u>.- The preliminary static tests were run on a Southwark-Emery universal hydraulic testing machine. The preliminary dynamic tests were run on a Riehle pendulum impact machine which is equipped for tension impact testing. Both of these machines have been described in a report of a previous study (reference 4).

The fatigue tests were run on an H. F. Moore type repeated direct stress machine (fig. 8) modified as necessary for this series. This machine has been described in reference 5. Several modifications were made in the Northwestern model both to handle the specimens used and also to insure the desired accuracy in dealing with the small loads desired. This machine is of the constant-strain type. With the eccentric set at zero, initial compression is applied to the specimen by tightening the calibrated helical spring. Tension to the desired amount then is applied through the proving ring. The eccentric then is set to give the proper amount of throw to the actuating lever bar which causes the load on the specimen to vary between the desired values of maximum tension and maximum compression. The calibration curve for the helical spring is shown in figure 9. A special dial gage was used to measure the spring extension, readings on two sides being averaged. The calibration curve for the proving ring is shown in figure 10, and in figure 11 is shown a calibration of the spring working against the ring and giving actual load delivered to the specimen. In determining the last two curves, two electric resistance wire strain gages mounted on opposite sides of a steel specimen placed in the testing machine, were used.

It was necessary to take a number of precautions to secure and hold the loads to the desired accuracy, some of which were as follows:

1. A specially selected and hardened tool steel eccentric was made, to avoid error from wear.

2. A buzzer was used to break up the friction in the proving ring dial indicator. The mounting and setting of this dial was never disturbed throughout the investigation.

3. The 0.007-inch shim steel diaphragms were slotted to avoid any dishing. The proper position of the ring shaft (lower end of specimen mount) to eliminate any vertical force in the diaphragms was determined by test and this position was marked by a special gage.

4. Care was used to avoid stresses due to change in room temperature.

5. Frequent checks of load on each specimen were made during a test and adjustments made when necessary.

6. Check of spring calibration at intervals showed no change.

The speed of the testing machine gives about 1600 reversals per minute. An investigation was made to determine whether vibration of the actuating lever might produce loads on the specimens differing appreciably from static loads. A dial indicator mounted on a micrometer screw and set in a frame rigidly bolted to the cast iron base of the testing machine at various stations along the lever was used. It was found possible to establish the fact that there was no deflection of the lever which would appreciably change the load on the specimen.

PRELIMINARY TESTS

The preliminary tests were made to investigate:

1. The strength of the shank for the purpose required

2. The possibility of a slip between the specimens and the grips

3. The static strength of the joints

The investigation of these questions was carried out in connection with an impact study recently made on the same series of joints, and the description of the preliminary tests is covered in detail in the report on that study. (See reference 4.)

The first two of the above questions were investigated through specimens of the preliminary tests. (See fig. 6.) The specimens were tested under both very slow static loads and impact loads. The specimen grips used were similar to the grips used in the main tests fatigue series (see fig. 12) except that the latter are longer and contain two dowel pins instead of one. Static strength tests were made on specimens of the main series. (See fig. 13.)

Preliminary Test Results

Strength of shank.- No weakness in the shanks of the specimens was discovered in any of the tests.

Slip in the grips.- The preliminary tests established the fact that no measurable slip of the specimens occurred either under static or impact loads. The evidence on this point was quite conclusive. The energy required to rupture the specimens varied from 0.4 foot-pound to 4 foot-pounds, due to the varying ratios of rivet diameter to plate thickness used, but the agreement between the energy required to rupture a given specimen type under static and under dynamic loads was remarkably good.

Static strength.– The static strength of the joints is recorded in table 1. The countersunk rivets for Method C with $h_b = -0.003$ showed the least strength, and the rivets for Method E showed the greatest strength; and there was a uniform variation of the strength from one type of rivet to another. The maximum difference in static strength was not large.

MAIN TESTS

It is generally agreed that the endurance limit for completely reversed stress and the static ultimate strength are the most significant properties since, from this information, the variation in fatigue strength with range of stress may be approximated by either a Goodman–Johnson (reference 6) or a Haig–Soderberg (reference 7) type of diagram.

The main purpose of the investigation was to establish by means of S–N diagrams the endurance limit at room temperature of each of the four types of specimen of the main test series.

Main Test Procedure

All main tests were run at room temperature. All specimens were subjected to completely reversed loading. The cycles at the endurance limit were carried to ten million or over for each type.

The procedure was to start a series with fairly high stresses, testing each specimen to rupture, and gradually reduce the stress on succeeding specimens until a point was reached where failure did not occur after ten million reversals.

Constant care at all stages was used. End connections were placed on a line scribed through the rivet center and all holes were drilled while the specimen was mounted in a jig. Careful watch was kept of the room temperature since the specimen would respond much more quickly than the machine to air temperature changes. As it was desired to hold the load constant on a given specimen throughout the test, frequent checking of the load was necessary with some slight adjustments at times.

A few joints were found with obviously defective rivets. These specimens held the static load during adjustment of the machine but failed after a few cycles of stress. In the CB series an unusually wide spread of results occurred just above the endurance limit, necessitating a large number of tests. In one or two cases the specimen failed not in the rivets but by fatigue fracture in the shank where the corner had been cut without a proper fillet.

Main Test Results

The results of the main tests are shown in table 1 and in figures 14 to 17. They are summarized in table 2 and figure 18. Enlarged photographs of typical rivet fractures are shown in figure 19.

Discussion of Main Test Results

The principal results of the main tests are as follows:

1. The static strength of the joints varied uniformly from 31,500 psi for type CA with $h_b = -0.003$ to 35,800 for type CC with $h_b = 0.010$ and 38,100 for type NA, reverse method.

2. The endurance limit (fatigue strength) varied uniformly from about 9,300 psi for type CA to 15,000 psi for type CC with type NA showing an intermediate strength of about 11,000 psi. This is a very substantial variation in strength.

3. In general, the S-N curves show the usual sharp break in the neighborhood of a million cycles of stress and a very gentle slope between one and ten million cycles.

4. The individual variation or spread in results in certain cases was quite broad, as is frequently the case in fatigue tests.

The most outstanding result of the tests is the effect of the method of riveting upon fatigue strength and, in particular, the low fatigue strength developed by the NA specimens, that is, reverse method. Equally interesting is the marked increase in fatigue strength as the value of h_b is increased.

Northwestern University,
Evanston, Ill., June 7, 1945.

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TABLE 1

FATIGUE TEST RESULTS

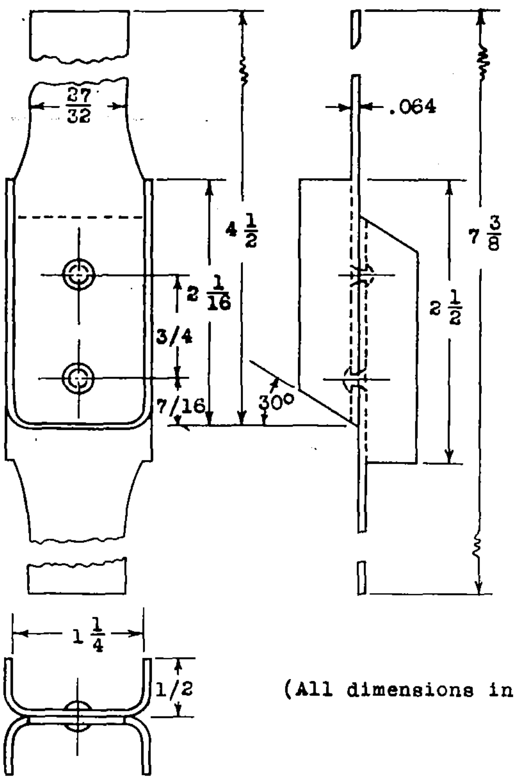
Specimen		Maximum load per rivet	Maximum unit stress	Number of cycles	Notes
Series	No	lb	psi		
NA	23	252	36 500		Static test
	24	263	38 100		" "
	37	263	38 100		" "
	38	262.5	38 000		" "
	39	206.5	37 100		" "
	40	263.5	38 100		" "
	16	111	16 100	16 400	Rivets ruptured
	17	96	13 900	60 000	" "
	18	92	13 350	230 000	" "
	19	85.5	12 400	200 000	" "
	20	78	11 300	3 000 000	" "
	26	78.5	11 400	600 000	" "
	27	78.5	11 400	410 000	" "
	28	79.5	11 500	1 014 000	Rivets loose
	29	76	11 000	10 000 000	Rivets not ruptured
	30	79.5	11 500	10 480 000	" " "
	31	97.5	14 150	2 470 000	" " "
	32	75.5	10 900	10 476 000	" " "
CA	24	217	31 500		Static test
	16	83	12 030	55 000	Rivets ruptured
	17	68.5	9 930	400 000	" "
	18	56	8 110	7 520 000	Rivets not ruptured
	19	81	11 750	235 000	Rivets ruptured
	20	63.5	9 200	6 042 000	Rivets not ruptured
	22	68	9 850	475 000	Rivets ruptured
	23	64	9 270	17 501 000	Rivets not ruptured
	26	64	9 300	11 100 000	" " "
	33	66	9 560	700 000	Rivets ruptured
	36	65.5	9 500	2 000 000	" "
CB	24	224	32 500		Static test
	38	223.5	32 400		" "
	20	92.5	13 400	14 251 000	Rivets not ruptured
	21	93	13 480	4 000 000	Rivets ruptured
	22	93.5	13 550	11 265 000	Rivets not ruptured
	25	90	13 050	1 347 000	Rivets ruptured
	26	96.5	14 000	1 135 000	Rivets ruptured
	27	110	15 950	83 000	Rivets ruptured
	29	104	15 100	42 000	Rivets ruptured
	30	100.5	14 550	108 000	Rivets ruptured
	31	98	14 200	28 300	Rivets ruptured

TABLE 1 (continued)

Specimen		Maximum load per rivet	Maximum unit stress	Number of cycles	Notes
Series	No	lb	psi		
	32	92.5	13 400	169 500	Rivets ruptured
	33	94.5	13 700	22 400	" "
	34	96	13 900	700 000	" "
	35	94.5	13 700	582 000	" "
	36	90.5	13 100	11 335 000	Rivets not ruptured
	37	93.5	13 550	371 000	Rivets ruptured
	39	94.5	13 700	190 000	" "
	41	92.5	13 400	300 000	" "
	42	93.5	13 550	1 400 000	" "
	43	95	13 760	1 270 000	" "
	44	98.5	14 280	800 000	" "
CC	37	245	35 500		Static test
	11	96	13 920	6 000 000	Rivets not ruptured
	12	104	15 100	12 210 000	" " "
	13	105.5	15 300	2 010 000	Rivets ruptured
	19	109	15 800	141 000	" "
	23	91	13 200	10 198 000	Rivets not ruptured
	24	94	13 600	5 976 000	" " "
	25	97	14 060	9 517 000	" " "
	26	131	19 000	425 800	Rivets ruptured
	27	124	17 960	1 792 000	" "
	28	103.5	15 000	9 175 000	Rivets not ruptured
	29	110.5	16 020	9 759 000	" " "
	30	123.5	17 910	6 632 000	" " "
	31	117.5	17 050	429 000	Rivets ruptured
	32	117.5	17 050	572 000	" "
	33	138.5	20 080	900 000	" "
	34	138	20 000	542 000	" "
	35	110.5	16 000	145 000	" "
	36	131	18 980	202 000	" "

TABLE 2.- SUMMARY OF MAIN TEST RESULTS.

	Series CA	Series CB	Series CC	Series NA
Static tensile strength psi	31 500	32 500	35 500	38 100
Endurance limit at 10^7 cycles psi	9 300	12 900	15 000	11 000
Ratio $\frac{\text{Static tensile strength}}{\text{Endurance limit}}$ %	30	40	42	29



Speci-men	Rivet diameter (in.)	Rivet-head angle (deg)	h_b	Method of driving	Depth of counter-sink	Number req'd.
CA1 to CA24	3/32	78	-0.003	C	0.050	24
CB1 to CB24	3/32	78	.000	C	.047	24
CC1 to CC24	3/32	78	.010	C	.037	24
NA1 to NA24	3/32	60	--	Reverse	.030	24

Figure 1.- Details of specimens for main tests.

(All dimensions in inches)

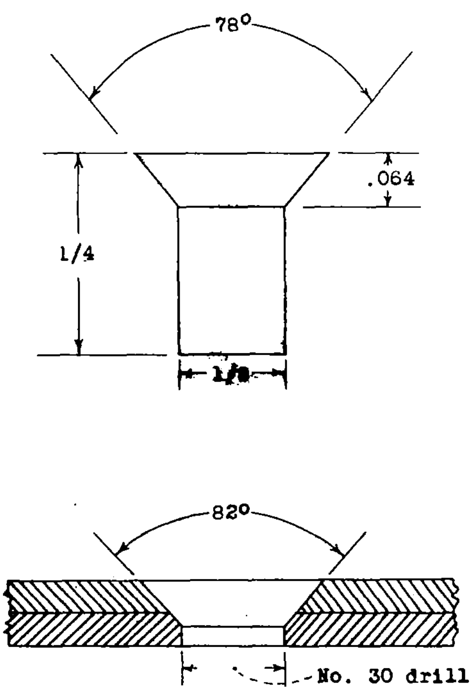


Figure 2.- Dimensions of machine-countersunk rivet and angle of countersink used in riveting method C for 1/8-in. rivet.

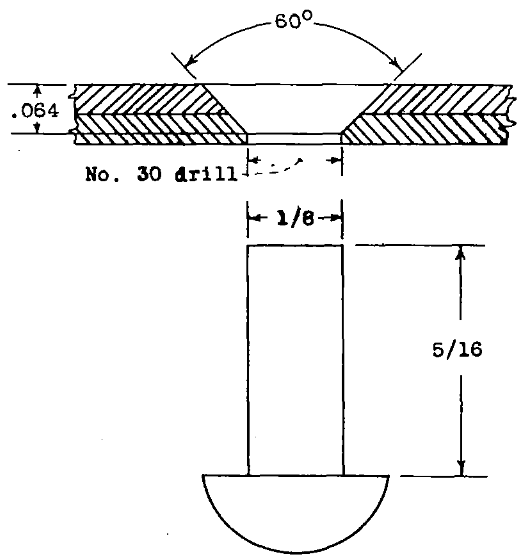
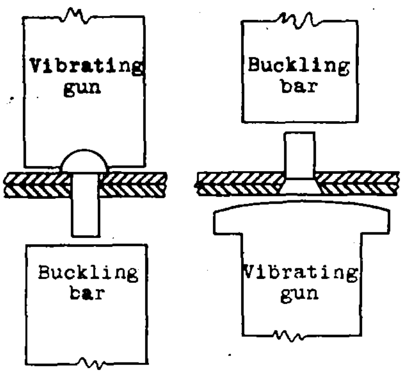


Figure 3.- Dimensions of roundhead rivet and angle of countersink used in riveting method E for 1/8-in. rivet.



Method E Method C

Figure 4.- Methods of riveting used in this investigation.

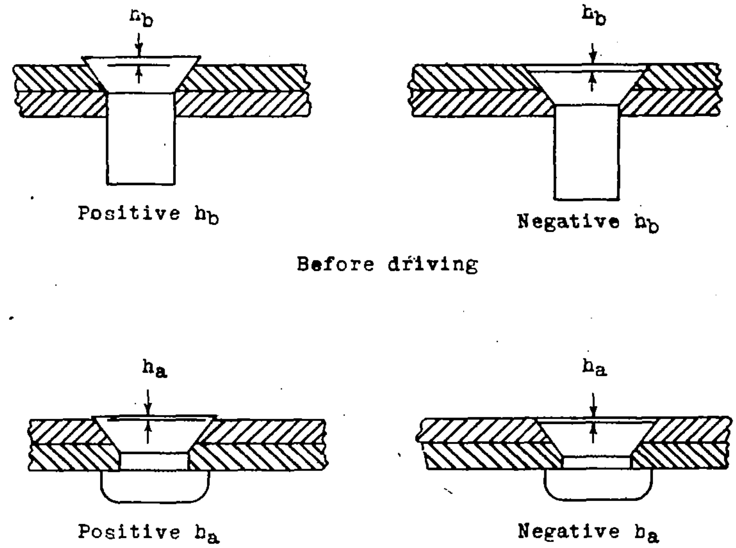
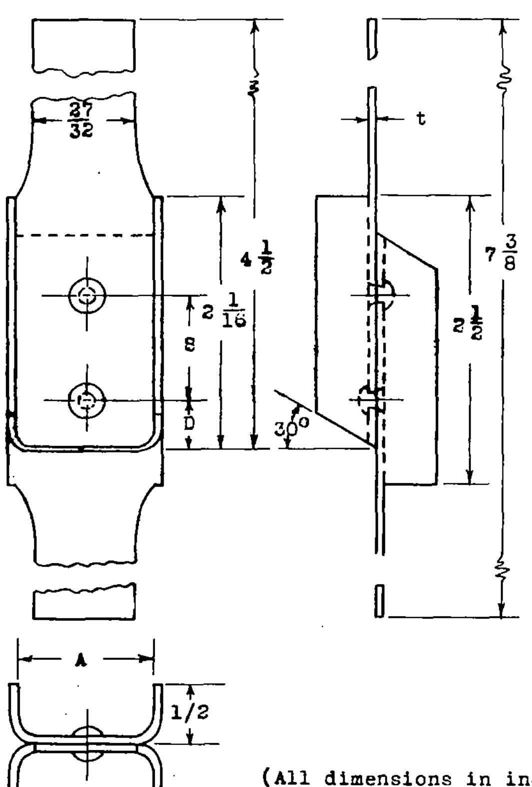


Figure 5.- Illustrations of h_b and h_a for machine-countersunk rivets.



(All dimensions in inches)

Specimen	Rivet diameter d (in.)	Sheet thickness t (in.)	S (in.)	D (in.)	A (in.)	Depth of countersink
Method C; h_b = 0; rivet-head angle, 78°						
C1A C1B	3/32	0.040	3/4	7/16	1-1/8	0.047
C2A C2B	3/32	.064	3/4	7/16	1-1/4	.047
C3A C3B	1/8	.040	7/8	3/8	1-1/8	.060
C4A C4B	1/8	.064	7/8	3/8	1-1/4	.060
Method E; rivet-head angle, 60°						
N1A N1B	3/32	0.040	3/4	7/16	1-1/8	0.030
N2A N2B	3/32	.064	3/4	7/16	1-1/4	.030
N3A N3B	1/8	.040	7/8	3/8	1-1/8	.050
N4A N4B	1/8	.064	7/8	3/8	1-1/4	.050

Figure 6.- Details of specimens for preliminary tests.

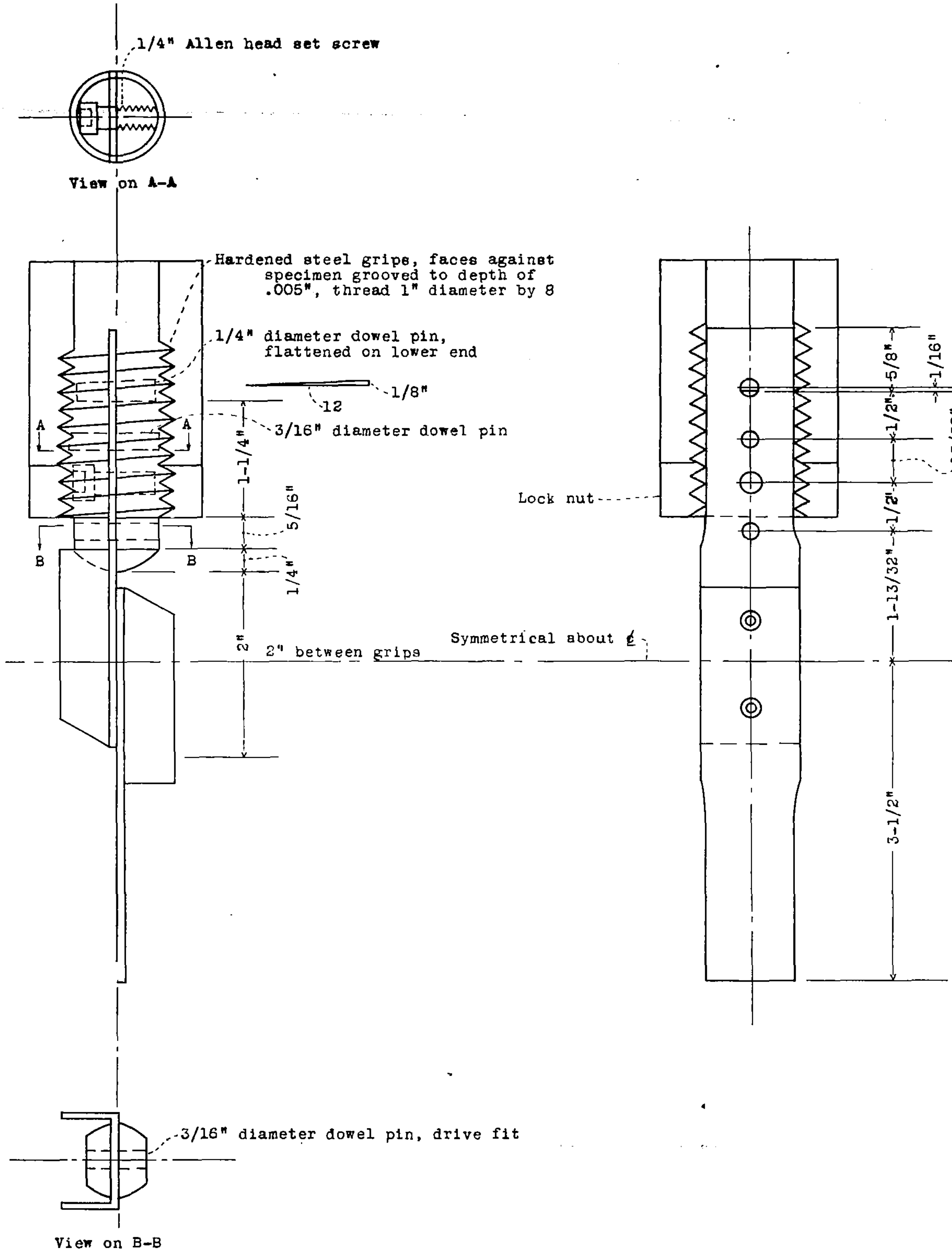


Figure 7.- Details of grips used to mount specimens in testing machines.

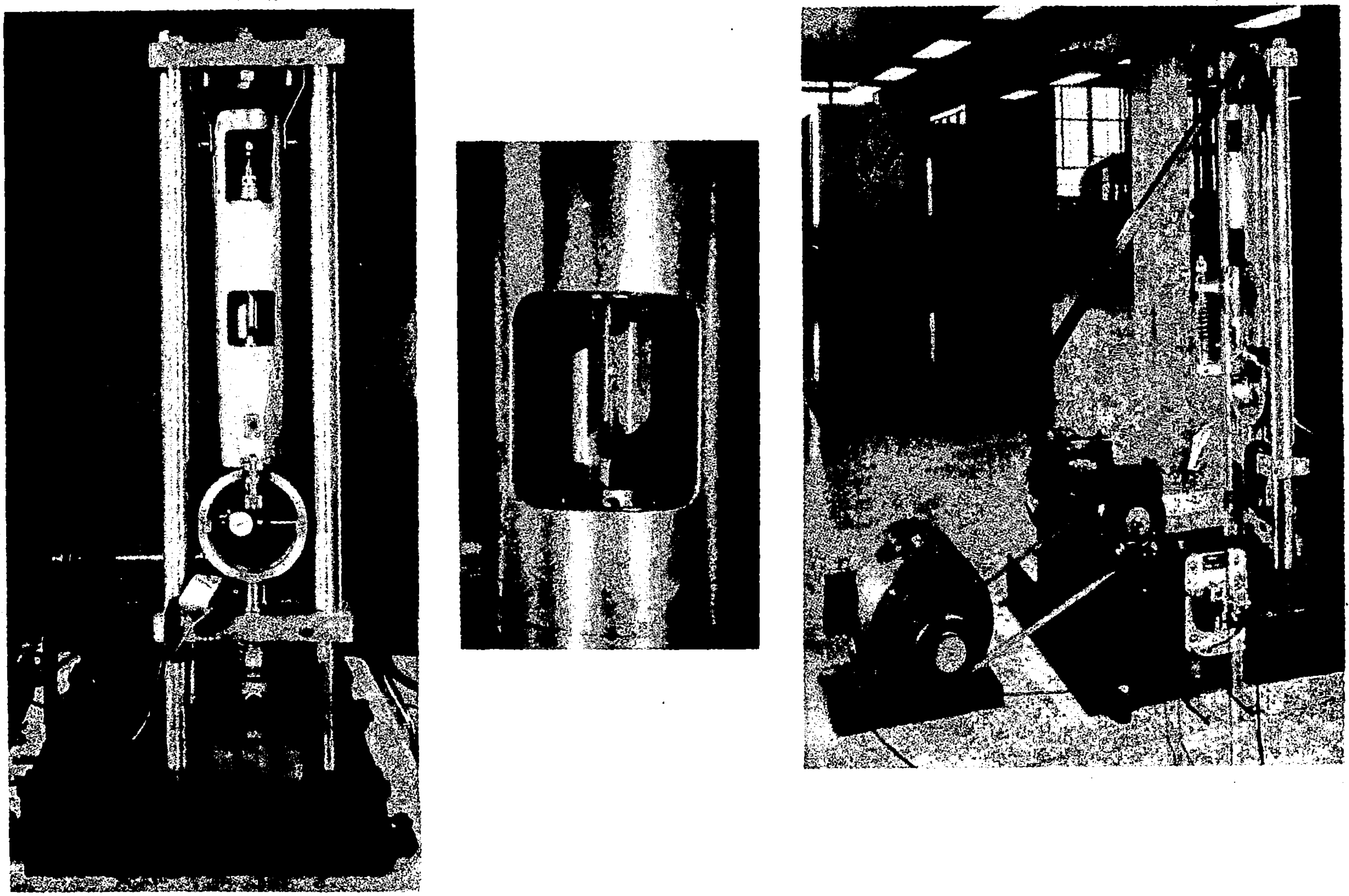


FIGURE 8.—H. F. Moore type fatigue machine.

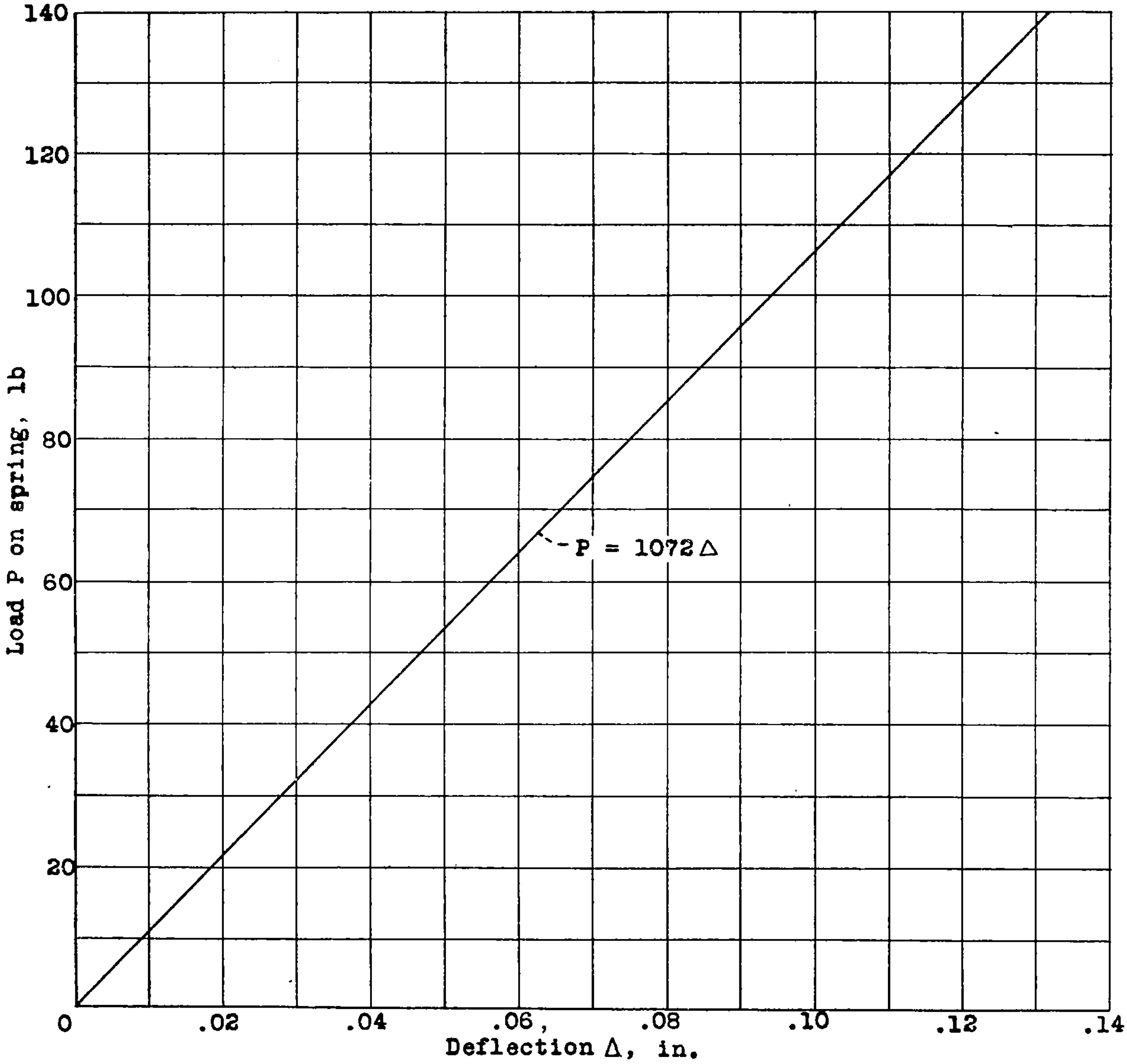


Figure 9.- Helical spring calibration graph.

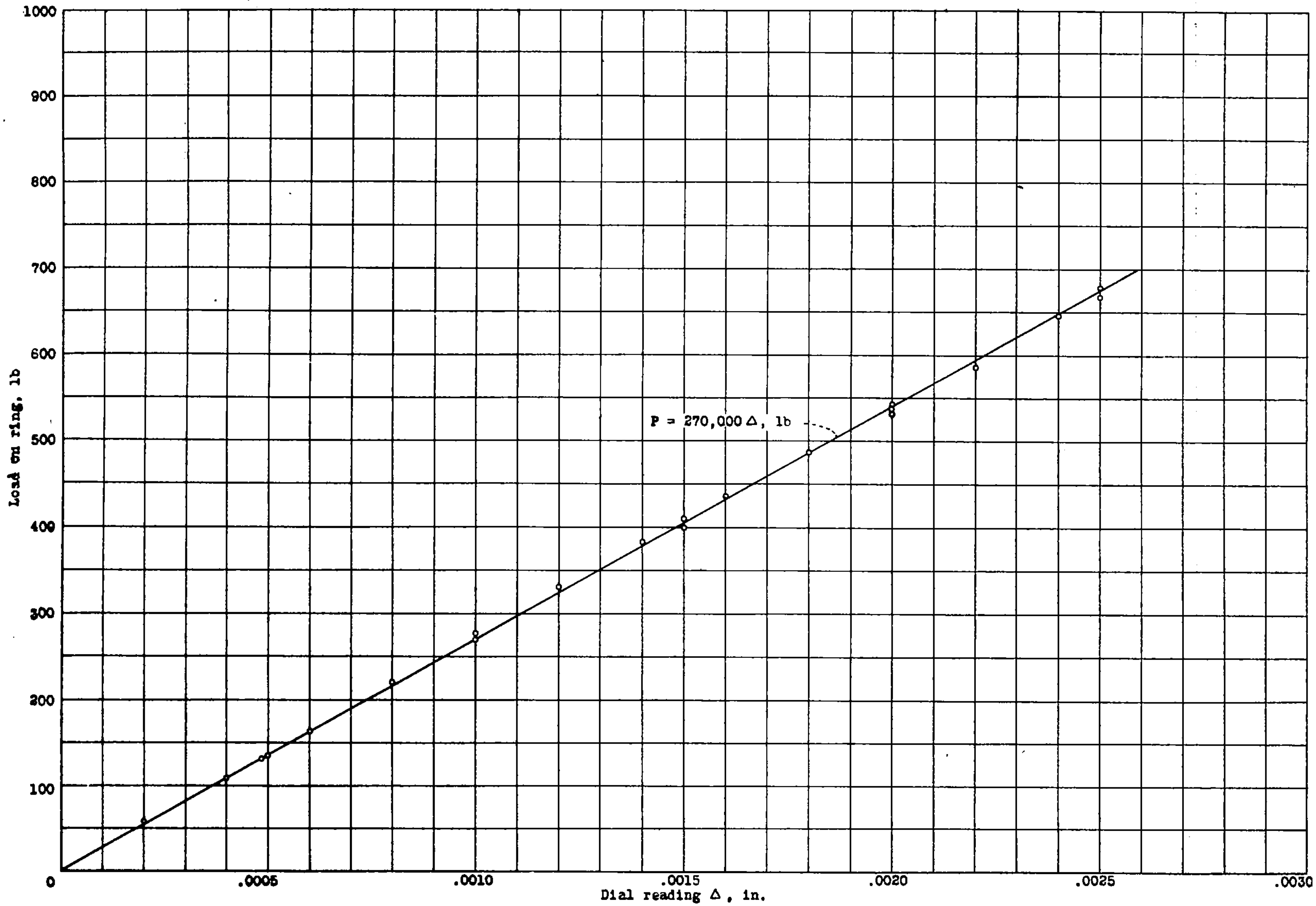


Figure 10.- Proving ring calibration. Calibration made using two electric resistance strain gages mounted on steel bar specimen in fatigue testing machine.

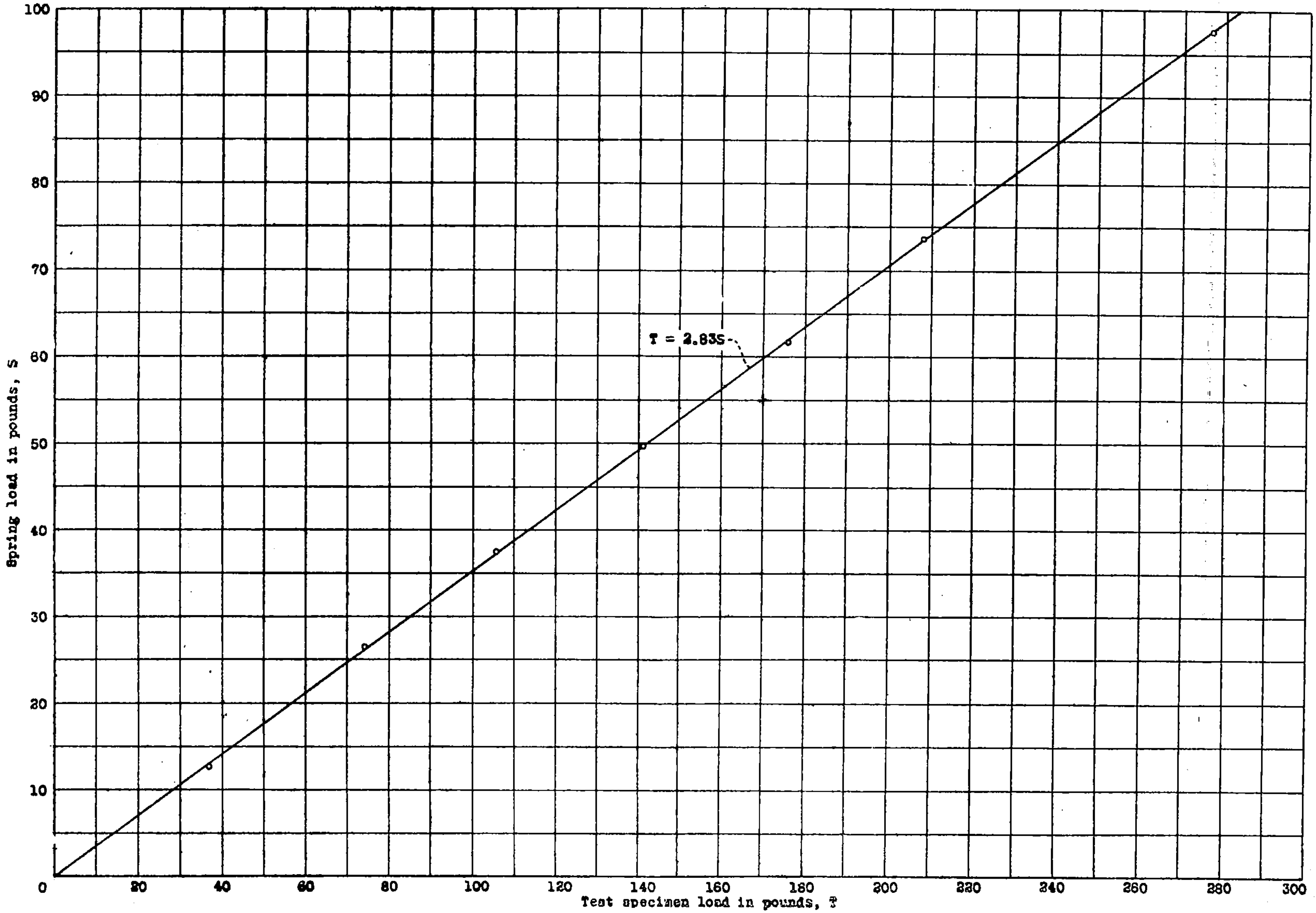
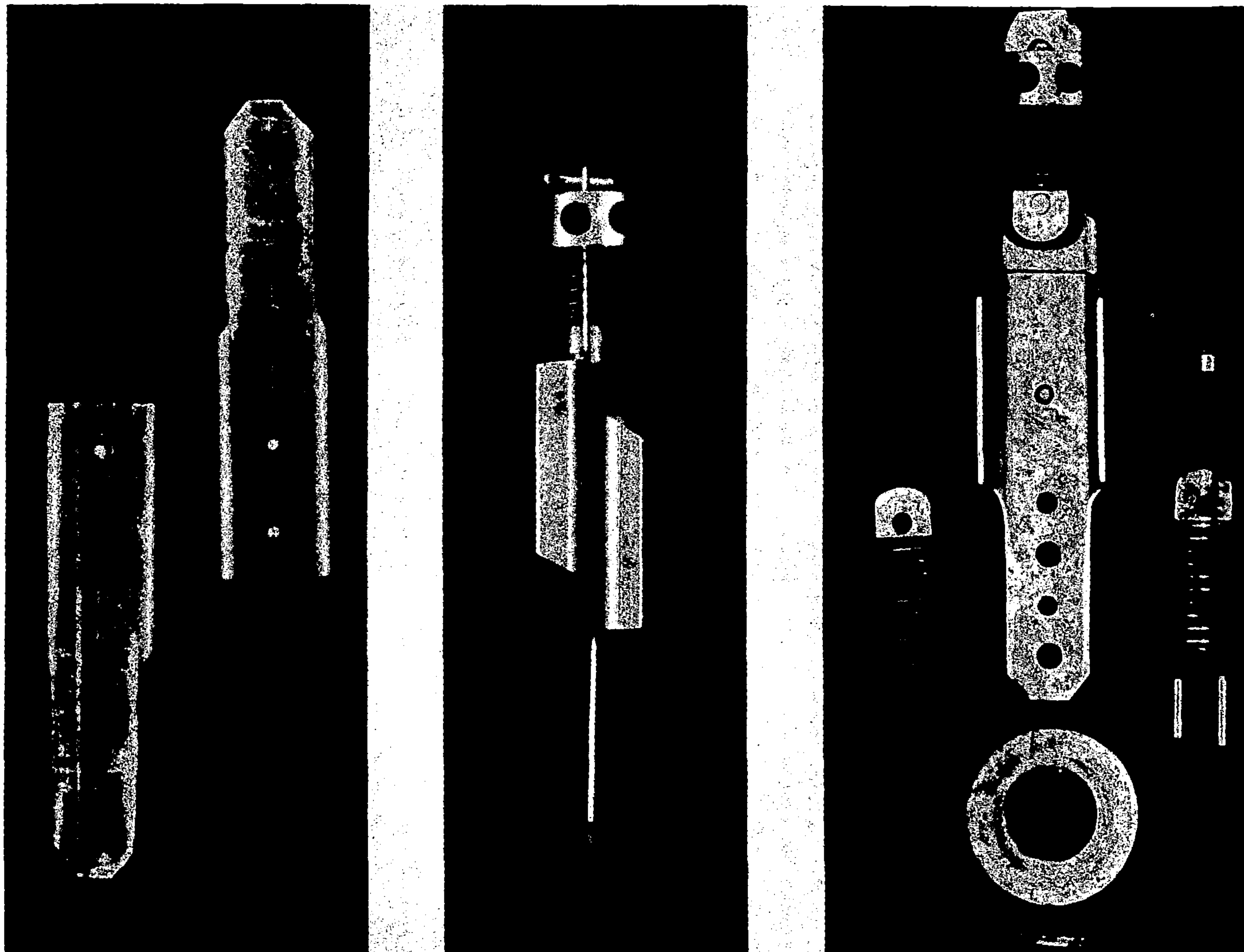


Figure 11.- Calibration of helical spring against proving ring. (Calibration made using two electric resistance strain gages mounted on steel bar specimen in fatigue testing machine.)



(a) Specimen CC35 after rupture (b) Specimen grips (c) Specimen grips

FIGURE 12.—Test specimen grips and details.

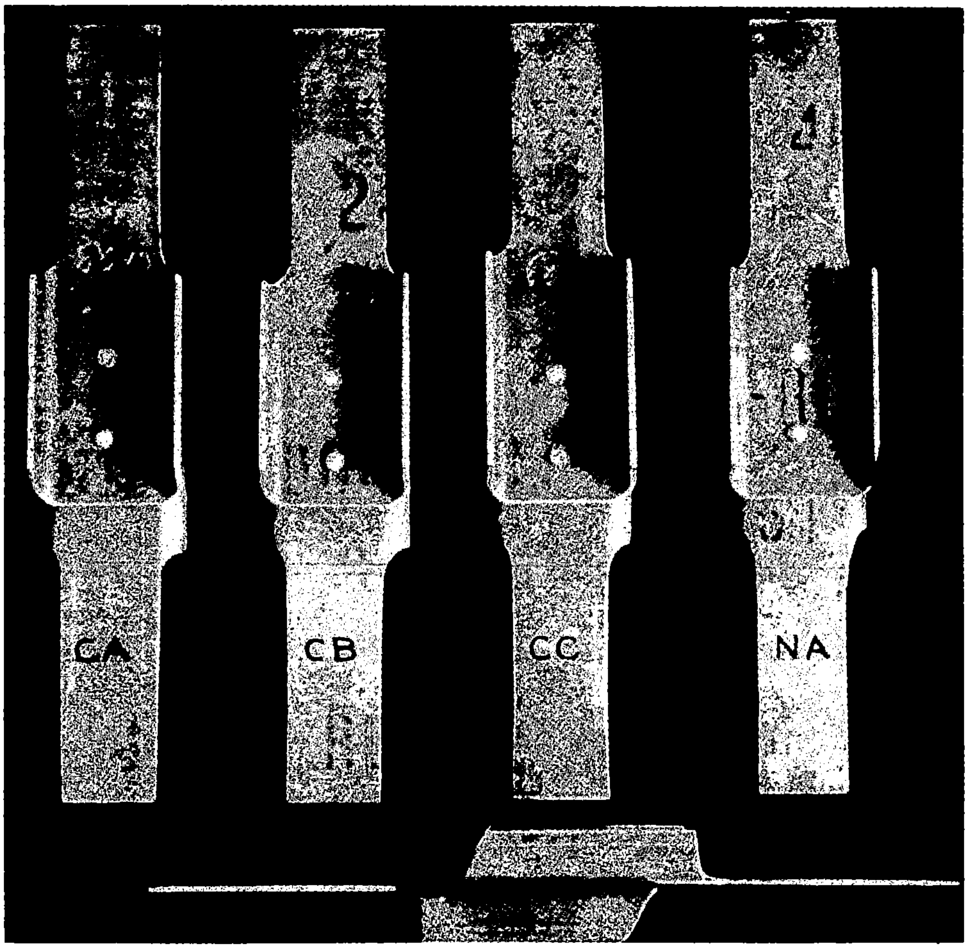


FIGURE 13.—Main test specimens before rupture.

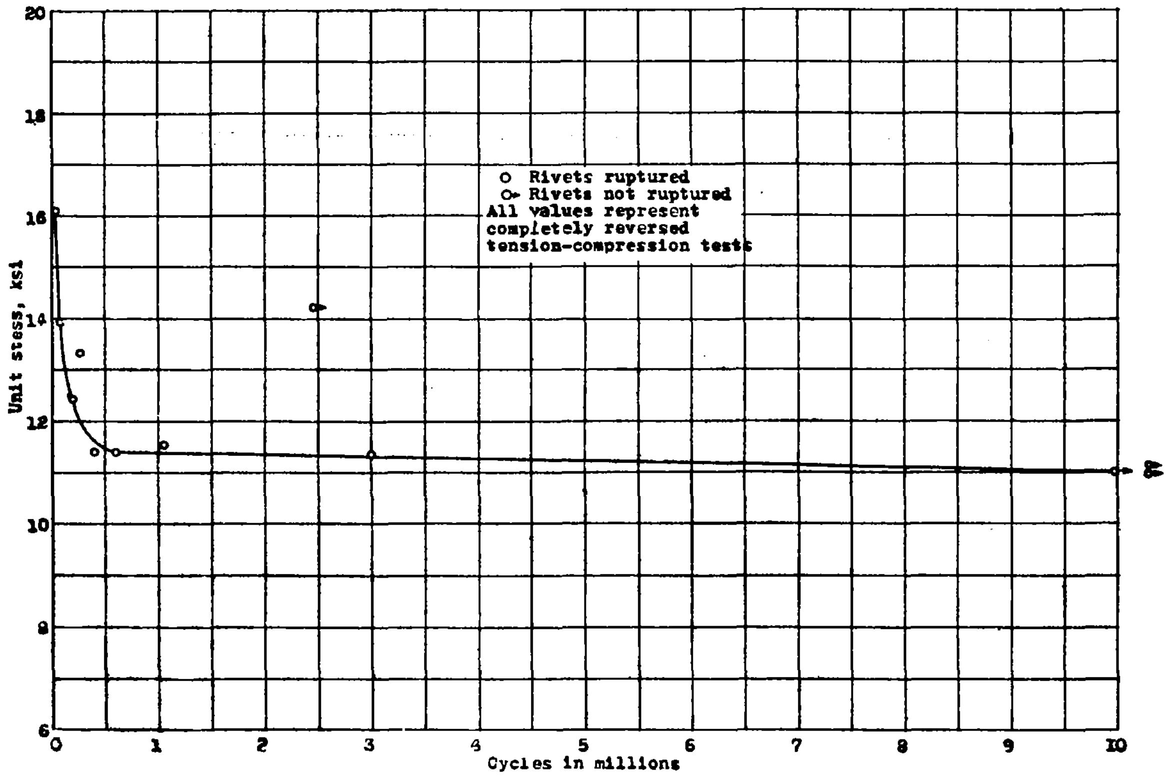


Figure 14.- S-N curve for NA specimens.

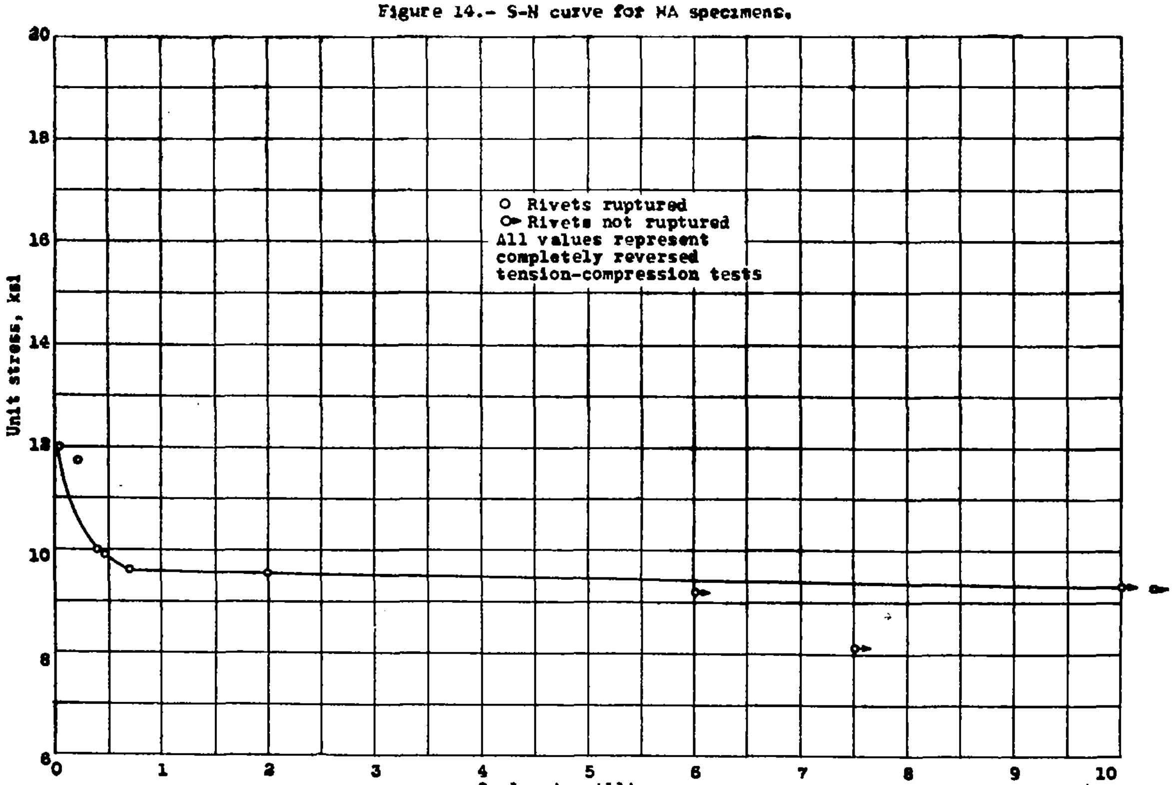


Figure 15.- S-N curve for CA specimens.

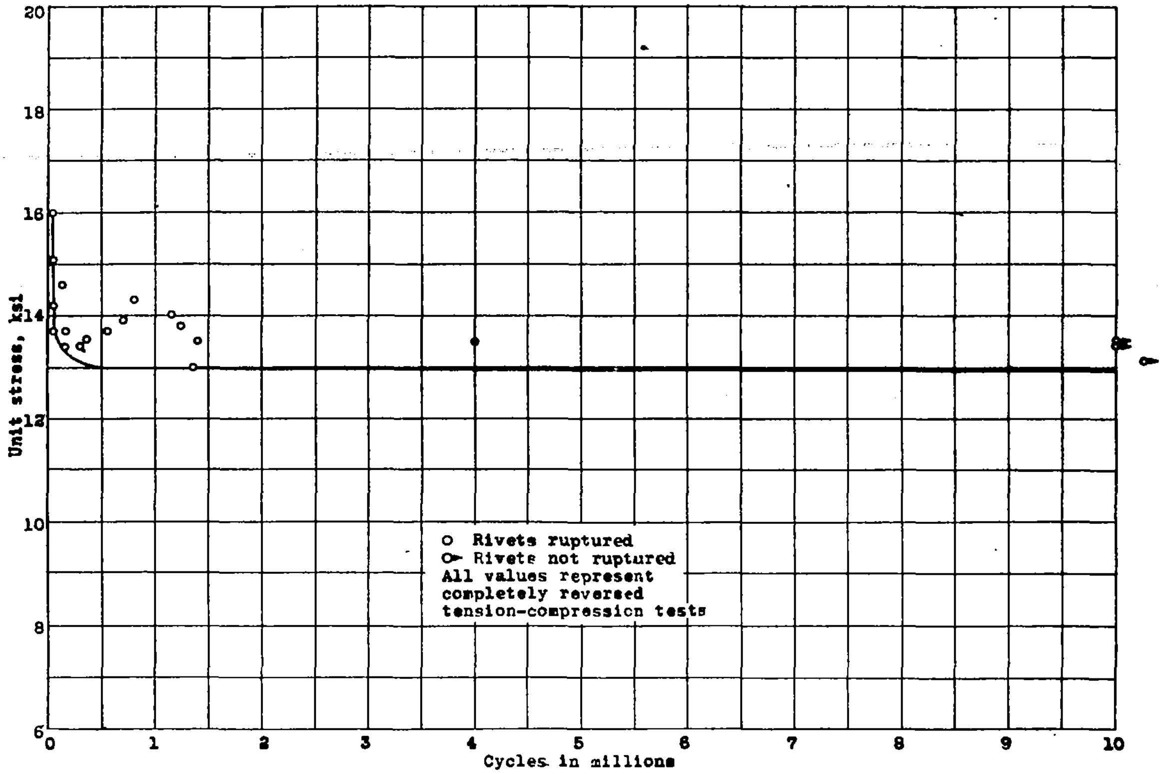
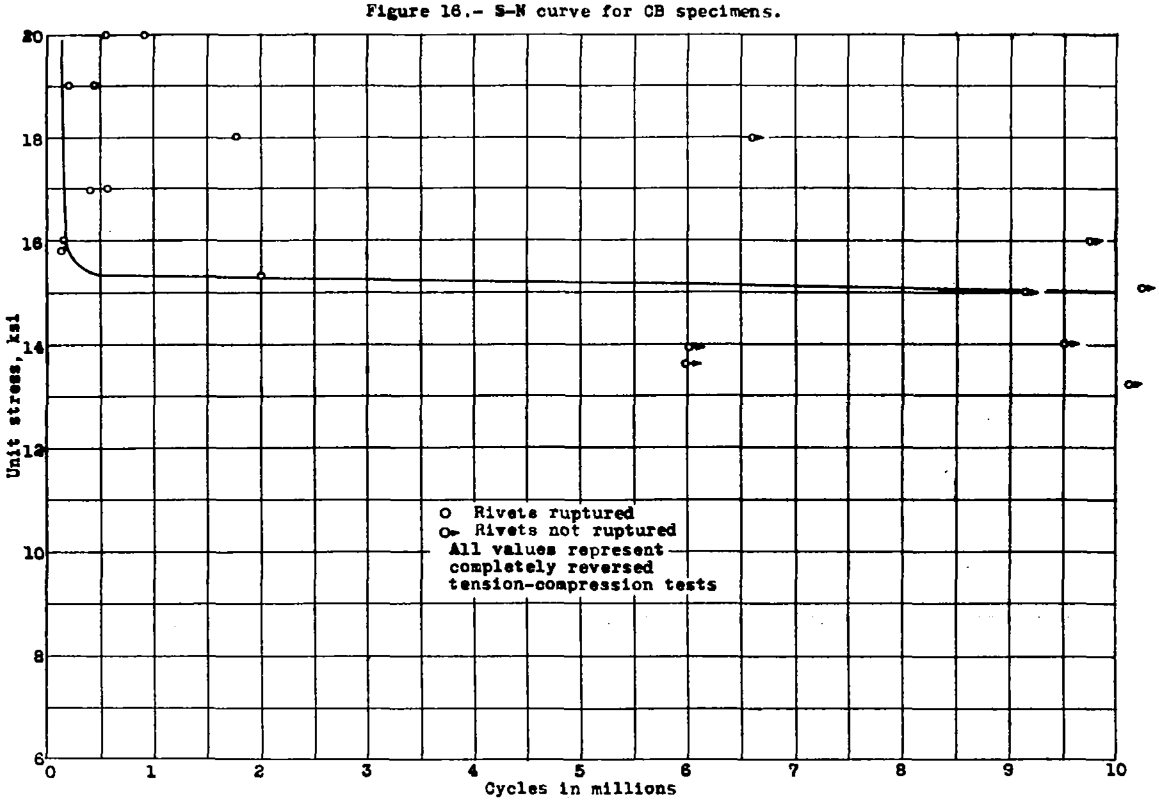
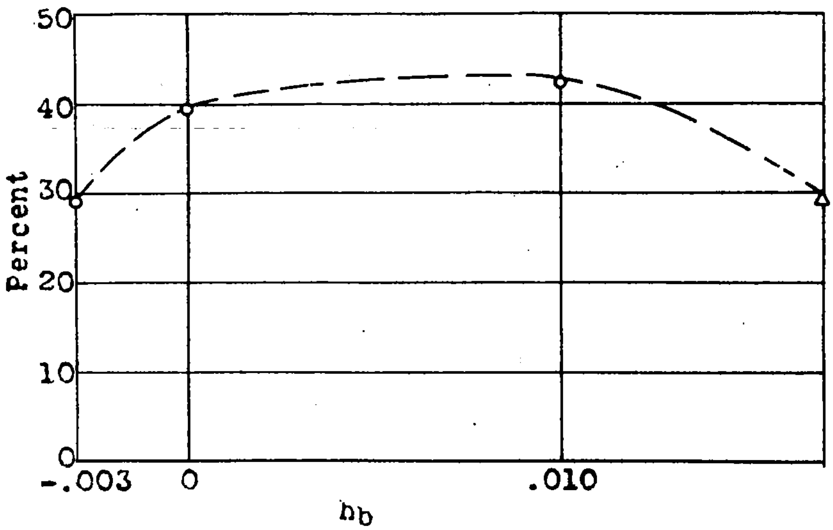
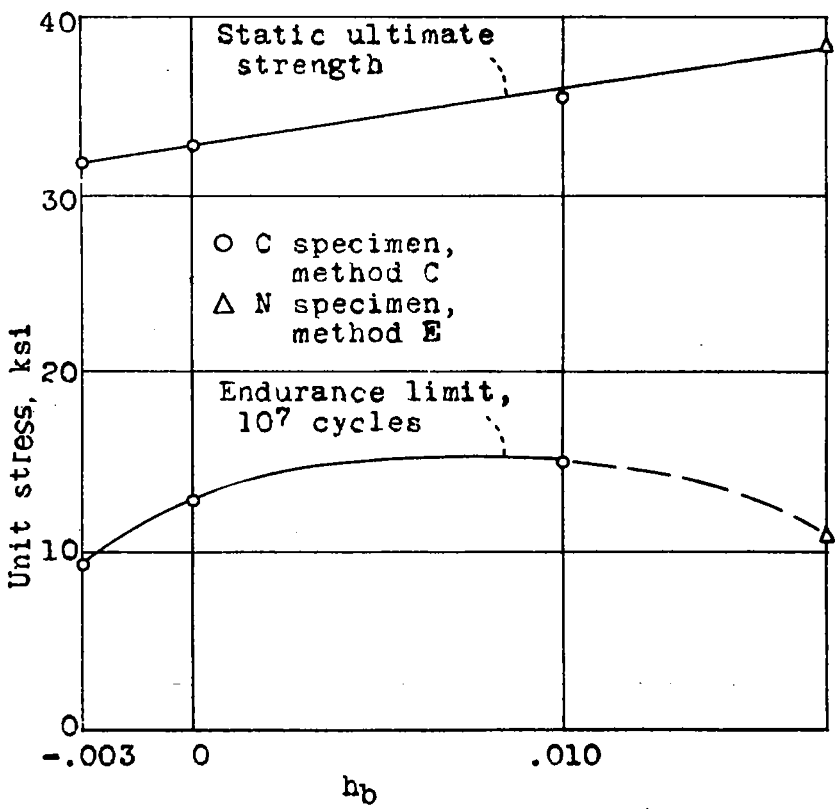


Figure 16.- S-N curve for CB specimens.



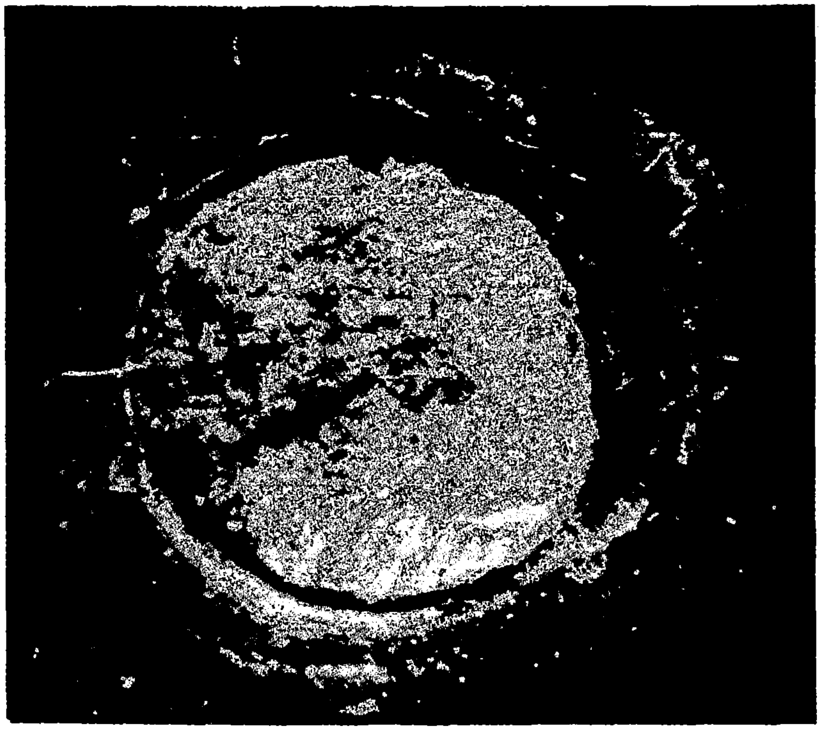


(a) Ratio $\frac{\text{Endurance limit, } 10^7 \text{ cycles}}{\text{Static ultimate strength}}$ in percent against h_b.

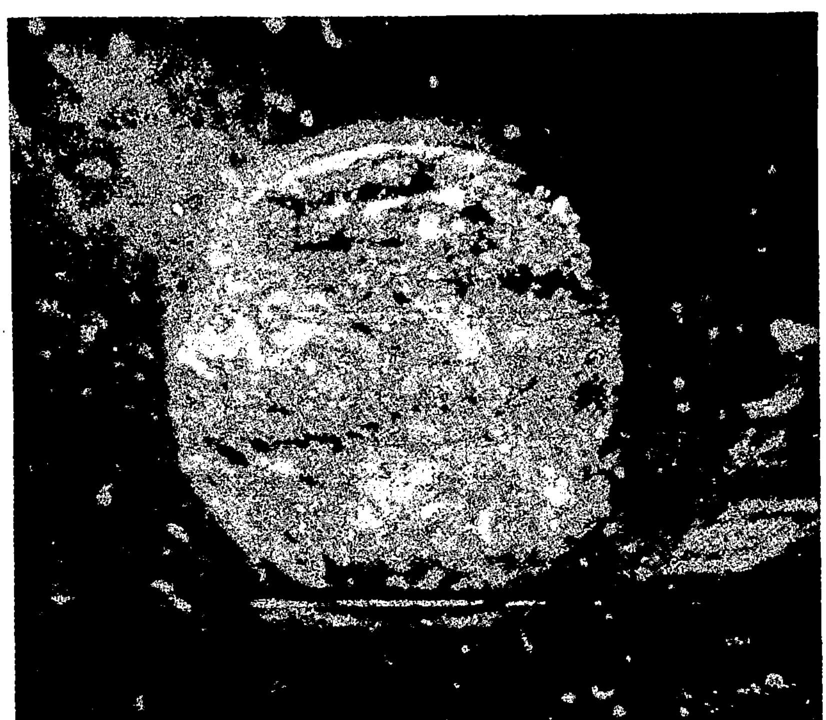


(b) Unit stress against h_b.

Figure 18.- Main test results.



Specimen CC35



Specimen CC35

FIGURE 19.—Main test rivets after rupture.